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A high frequency search for radio pulsars in three EGRET error boxes

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ABSTRACT
We present a new survey for pulsars in the error boxes of the low-latitude EGRET sources 3EG J1027−5817, 3EG J1800−2338 and 3EG J1810−1032. Although all of these sources have been covered by previous pulsar surveys, the recent discovery of the young, energetic pulsar PSR J1410−6132 at 6.7 GHz has shown that pulsars of this type can be hidden from low frequency surveys. Using an observing frequency of 3.1 GHz we discovered a 91-ms pulsar, PSR J1028−5819, which observations made at the Parkes telescope and the Australia Telescope Compact Array have shown to be young and energetic. We believe this pulsar is likely to be powering the unidentified EGRET source 3EG J1027−5817. Like other energetic pulsars, PSR J1028−5819 is highly linearly polarised, but astonishingly has a pulse duty cycle of only 0.4%, one of the smallest in the entire pulsar catalogue.

Key words: pulsars: general — pulsars: searches — pulsars: individual: J1028−5819 — pulsars: timing

1 INTRODUCTION

The EGRET telescope on board the Compton Gamma-Ray Observatory detected several hundred gamma-ray sources, of which around half do not have a well established identification with any known object. The true nature of these unidentified sources has been a matter for much debate (e.g. Hartman et al. 1999; Kramer et al. 2003) but the typically degree size error boxes of the sources has make identification at other wavelengths difficult. Pulsars are good candidates for many of the unidentified sources in the Galactic plane, as they have a similar spatial distribution and are one of the few populations of astronomical objects positively identified as gamma-ray emitters. Indeed, a number of recently discovered young pulsars are spatially coincident with unidentified EGRET sources (Torres et al. 2001; Kramer et al. 2003) but whether they pulse in gamma-rays will only be determined following the launch of GLAST (Smith et al. 2008).

The recently discovered pulsar PSR J1410−6132 (O'Brien et al. 2008), which is coincident with a previously unidentified EGRET source, was recently detected as part of a Galactic plane survey carried out at the high frequency of 6.5 GHz. PSR J1410−6132 was not discovered by surveys at lower frequencies because it suffers from severe scatter broadening which renders the pulse invisible. It is therefore sensible to assume that other Galactic-plane EGRET sources may be associated with pulsars that are not yet known due to obscuration from interstellar scattering. To this end we carried out a survey of Galactic-plane EGRET sources using a high frequency receiver at the Parkes radio telescope. Although PSR J1410−6132 was discovered using a 6.5 GHz multibeam system, we decided to employ a wide-band 3 GHz receiver. The frequency was chosen as a compromise between the interstellar scattering effects, which decrease as ν^{-4}, the typical pulsar spectral index (flux density decreases as $\nu^{-1.6}$, e.g. Lorimer & Kramer 2005), and the number of pointings required to cover the large error boxes of the EGRET sources.

In Section 2 of this paper we present our survey of three unidentified galactic-plane EGRET sources. In Section 3 we describe the discovery of the young, energetic pulsar PSR J1028−5819. Finally in Section 4 we discuss the emission properties of J1028−5819 and the possible association between the new pulsar and the EGRET source 3EG J1027−5817.

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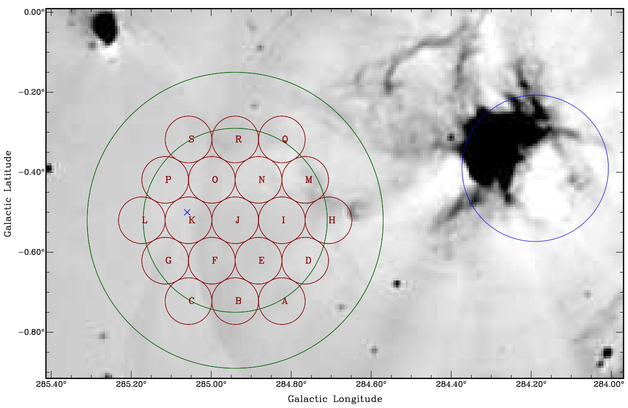

Figure 1. The pattern of 19 beams used to survey the error box of 3EG J1027−5817. The 1-σ and 2-σ error circles are shown by the larger concentric circles. The underlying image is an 843 MHz radio map from the Molonglo Galactic Plane Survey (Green et al. 1999). The position of PSR J1028−5819 in beam K is marked with a cross and the position of the nearby HESS source J1023−575 (Aharonian et al. 2007) is marked with the blue circle to the right of the figure.

2 SURVEY OBSERVATIONS AND ANALYSIS

2.1 Observation strategy

We selected from the 3EG catalogue those sources with an absolute galactic latitude of less than 5° and a variability index, as discussed by McLaughlin et al. (1996), less than 2. This reduces the original 269 sources to just 31 and includes the known gamma-ray pulsars such as Vela and PSR B1706−44 and likely candidates such as PSRs B1046−58 and J1420−6048. We then chose sources such that they were visible with the Parkes telescope and that the error circle was less than 0.4° in radius, so that the 2-σ error box could be filled with less than 20 pointings. This resulted in our final selection of three sources: 3EG J1027−5817, 3EG J1800−2338 and 3EG J1810−1032. As a confirmation, we repeated this process using the updated variability index suggested by Nolan et al. (2003) and produced the same three sources. Each source was covered with 19 separate pointings; those for 3EG J1027−5817 are shown in Figure 1.

Observations were carried out between 2008 April 6 and 9 at the Parkes radio telescope using the 10cm band of the dual '10–50' receiver at a centre observing frequency of 3.1 GHz. This was connected to a 288 channel filterbank system with a total bandwidth of 864 MHz, 1-bit sampled in total intensity every 250 μs and recorded to tape for off-line processing. Each beam on the sky was observed for a total of 18 minutes. The 10cm receiver has a system equivalent flux density of 45 Jy and our sensitivity limit for pulsars with a 10% duty cycle and low dispersion measure was therefore 0.2 mJy.

2.2 Analysis and results

The recorded data were processed using software based on the SIGPROC[1] package. Each pointing was dedispersed to 768 trial dispersion steps, up to a maximum of 1333 cm^{-3}pc. Periodicities in the target file were then identified using a fast Fourier transform based algorithm. The results were then collated into a number of candidates and optimised in the time domain using the PULSARHUNTER software (Keith 2007). Candidates were then viewed using JREAPER (Keith et al., in preparation), to select the best candidates for re-observation.

This analysis resulted in one good candidate pulsar; immediate re-observation at Parkes confirmed that this was a genuine detection, and the new pulsar was designated PSR J1028−5819.

3 PSR J1028−5819

PSR J1028−5819 was detected on 2008 April 6 in beam K (as labelled in Figure 1) with a dispersion measure of 96 pc cm^{-3}, during initial processing carried out at the telescope. The detected pulse period of 91.4 ms immediately indicated that the pulsar was likely to be a young energetic pulsar and therefore potentially associated with its EGRET source.

3.1 Observations and results

Observations of the pulsar were made on 2008 April 9 with the Australia Telescope Compact Array (ATCA), an east-west synthesis telescope located near Narrabri, NSW, which consists of six 22-m antennas on a 6 km track. The observations were carried out simultaneously at 1.4 and 2.4 GHz with a bandwidth of 128 MHz at each frequency subdivided into 32 spectral channels, and full Stokes parameters. Total observation time on source was 120 min. The ATCA is also capable of splitting each correlator cycle into bins corresponding to different phases of a pulsar's period, and in our case the pulse period of ~91 ms was split into 32 phase bins. This allows a search to be made for the pulsar over the field of view of the primary beam (40′) of the telescope.

Initial data reduction and analysis were carried out with the MIRIAD package using standard techniques. After flagging bad data, the primary calibrator (PKS 1934−638) was used for flux density and bandpass calibration and the secondary calibrator (PMN J1051−5344) was used to solve for antenna gains, phases and polarisation leakage terms. After calibration, the data consist of 13 independent frequency channels each 8 MHz wide for each of the 32 phase bins. The data were then de-dispersed using the known dispersion measure.

From analysis of the interferometric data we determined the pulsar's position to be at right ascension 10:28:28.0 $\pm$ 0.1 and declination −58:19:05.2 $\pm$ 1.5 in the J2000 coordinate system. The pulsar has a flux density of 0.36 $\pm$ 0.06 and 0.52 $\pm$ 0.06 mJy at 1.4 and 2.4 GHz respectively. The pulsar therefore appears to have a rather flat spectral index, but we

[1] http://sigproc.sourceforge.net/

Table 1. Timing parameters obtained for PSR J1027−5819. Figures in parentheses are the nominal 1σ TEMPO2 uncertainties in the least-significant digits quoted.

Pulsar name	J1028−5819
Right ascension, α	10:28:28.0
Declination, δ	−58:19:05.2
Pulse period, P (ms)	91.4032309(14)
Period derivative, $\dot{P}$	$16.1(8)\times10^{-15}$
Pulse frequency, ν (s^{-1})	10.94053230(16)
Frequency derivative, $\dot{\nu}$ (s^{-2})	$-1.92(9)\times10^{-12}$
Dispersion measure, DM (cm^{-3}pc)	96.525(2)
Epoch of fit (MJD)	54562
$\log_{10}$(Characteristic age, yr)	4.95
$\log_{10}$(Surface B field strength, G)	12.09
$\log_{10}$(Energy loss rate, $\dot{E}$)	35.91
DM derived distance (kpc)	2.3
MJD range of fit	54563.6—54606.2
Number of TOAs	20
Rms timing residual (μs)	4.5
Clock correction procedure	TT(TAI)
Solar system ephemeris model	DE405

caution that this single flux measurement could be affected by scintillation.

Further observations of the pulsar were carried out using the Parkes radio telescope at 1.4 and 3 GHz using the centre beam of the 20cm-multibeam and 10–50 receivers respectively. A digital filterbank was used to record integrated profiles with full Stokes information every 30 s with 1024 channels over a 256 or 1024 MHz band at 1.4 and 3 GHz respectively. In parallel, the data were sampled every 250 μs in total intensity using the 512 channel analogue filterbank.

The data were then further processed using standard pulsar timing techniques to yield 20 good time-of-arrival (TOA) measurements and integrated polarisation profiles. The pulsar spin frequency, frequency derivative and dispersion measure were then fit to the TOAs using the TEMPO2 software package whilst holding the pulsar's position fixed. From the timing analysis, we constrain the pulsar parameters as shown in Table 1. This implies a characteristic age of 90 kyr, surface magnetic field strength of 1.2×10^{12} G and a spin down energy rate of 8.3×10^{35} erg s^{-1}. Using the measured dispersion measure and the Cordes & Lazio (2002) electron-density model, we derive a distance to the pulsar of 2.3 kpc.

3.2 Polarisation profiles and single pulses

The integrated profiles for PSR J1028−5819 at 1.4 GHz and 3.1 GHz are shown in Figure 2. We were unable to detect the pulsar during a 10 min observation at 0.61 GHz, likely due to a combination of the pulsar's relatively flat spectral index, the increased sky brightness temperature at this low frequency and radio interference. We used the 20 cm observations to determine the rotation measure of the pulsar to be -5 ± 4 rad m^{-2}.

The profiles show that the pulse is a narrow double, with the leading component weaker than the trailing component but with a flatter spectral index. Both components are virtually 100 per cent linearly polarised and there is little circular polarisation. These characteristics are typical of young, energetic pulsars (e.g. Johnston & Weisberg 2006 and Weltevrede & Johnston, in preparation). The position angle is almost completely flat across the entire profile.

Unlike other energetic pulsars, the width of the profile of PSR J1028−5819 is remarkably narrow. The two components have a half-power width of only 175 μs and 160 μs for the leading and trailing peaks respectively. The separation of the components is 330 μs and the 10% power width of the entire profile is 560 μs. This duty cycle of just 0.4% appears to be the smallest of any integrated profiles of the known pulsars.

We note that this small duty cycle is akin to that of the RRATs (McLaughlin et al. 2006) which show very bright pulses followed by long period nulls. Johnston & Romani (2002) and Weltevrede et al. (2006) showed that some so-called normal pulsars often showed narrow, bright pulses quite distinct from the normal single pulses. We therefore examined 6500 single pulses from PSR J1028−5819 to look for evidence of similar behaviour. However, the pulsar's flux does not appear to be strongly modulated and we detected no single pulses with a flux density greater than 10 times the mean on-pulse flux density.

4 DISCUSSION

4.1 Association with 3EG J1027−5817

The pulsar dispersion measure can be used to estimate the distance to the source by using a model of the galaxy electron density. Using the model of Cordes & Lazio (2002), the estimated distance to the pulsar is 2.3 kpc.

The spin down rate of PSR J1028−5819 implies a rotational energy loss rate $\dot{E} = 8.3 \times 10^{35}$ erg s^{-1}. At a distance of 2.3 kpc we compute the value $\dot{E}/d^2$, a good indicator of gamma-ray detectability, to be 1.6×10^{35} erg s^{-1} kpc^{-2}, which is in the top 20 of all known pulsars.

By fixing the distance to the EGRET source at the pulsar distance we can compute the power output of the gamma-ray source. This distance plus the published photon count rate of 6.6×10^{-7} photons cm^{-2} s^{-1} and photon spectral index of 2 for 3EG J1027−5817 (Hartman et al. 1999) implies a gamma-ray energy-loss rate of 2.5×10^{34} erg s^{-1}, with an assumed beaming angle of $1/(4\pi)$. This implies that if the pulsar is powering the EGRET source then $\sim 3\%$ of the pulsar spin down energy must be going into gamma-ray flux. This is consistent with the percentage seen in other gamma-ray pulsars (as discussed by e.g. O'Brien et al. 2008) and we therefore claim that PSR J1028−5819 is indeed the source responsible for the gamma-rays from 3EG J1027−5817.

Confirmation or rejection of this hypothesis will be possible with the upcoming GLAST mission. This will be able to both confirm the nature of the EGRET source and to further measure the gamma-ray properties of the pulsar. In order to provide accurate rotational ephemeris for gamma-ray folding, we will continue to monitor the pulsar in the radio band.

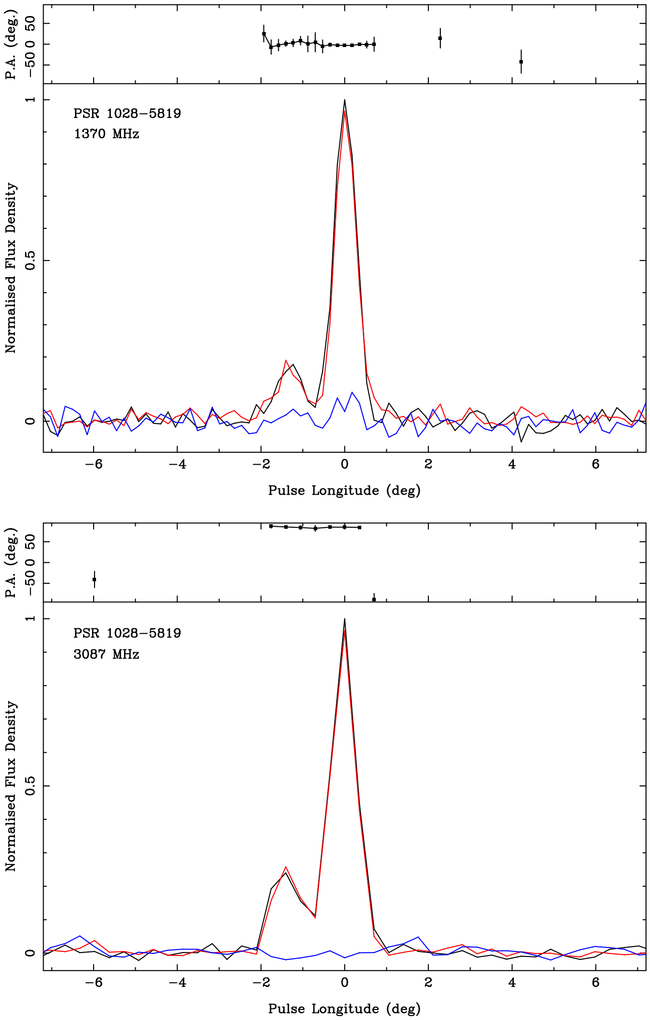

Figure 2. Integrated pulse profile of J1028−5819 at 1.4 GHz (top) and 3.1 GHz (bottom). Total intensity is shown in black, with linear polarisation in red and circular polarisation in blue. The polarisation position angle variation over the pulse is shown in the upper panel. The polarisation position angles shown are not absolute. The 1.4 GHz profile is generated by summing four 4.5-minute observations taken at Parkes on 2008 April 15 with 2048 bins over the entire profile. The 3.1 GHz profile is produced from a single 6-minute observation taken at Parkes on 2008 April 9, with 1024 bins across the profile.

4.2 Multi-wavelength data and possible associations

As shown in Figure 2, PSR J1028−5819 is easily detectable at 1.4 GHz with minimal scattering effects. Since its position is within the bounds of the Parkes Multibeam Pulsar Survey (Manchester et al. 2001), an investigation was carried out to determine why this pulsar was not discovered in the original survey. Inspection of the observation logs and data archives shows that technical issues meant that data from the survey observation covering the pulsar were never processed. We obtained these data, taken on 2004 October 10, and the pulsar was indeed detected with a signal-to-noise ratio of 25.

In the X-ray band, data from the ROSAT All-Sky Survey does not show any significant emission at the pulsar position. However observations with more sensitive instruments should be undertaken to determine whether the pulsar is an X-ray emitter and/or uncover the presence of an underlying X-ray pulsar wind nebula.

PSR J1028−5819 is located just 1° away from the HESS source J1023−575, although the latter is likely associated with the stellar cluster Westerlund 2 (Aharonian et al. 2007). However, we can consider the possibility that the HESS source was powered by PSR J1028−5819 sometime in the past. If the pulsar was born at the HESS source position, using the DM derived distance and the characteristic age as true values, we compute a transverse velocity of ~ 500 km s^{-1}. This is somewhat high, but not outside of the observed range of known pulsar velocities. The distance to Westerlund 2 is not well known, although most estimates put it at around 8 kpc (e.g. Rauw et al. 2007) which is considerably further than our estimated distance to the pulsar. At this time we do not have any evidence to suggest that PSR J1028−5819 is related to HESS J1023−575 or Westerlund 2, however the small angular separation should be noted.

4.3 Implications of small duty cycle

Like many other young, energetic pulsars, PSR J1028−5819 is highly polarised and shows a double peaked profile (e.g. Weltevrede & Johnston, in preparation). However, the pulsar has an unusually small duty cycle, more than an order of magnitude smaller than the norm. How does this fit into our picture of pulsar beams?

Since the profile is double peaked with similar pulse widths for both leading and trailing parts, we can hypothesise that we are cutting through a cone of emission, as in the typical pulsar emission scenario. If we assume that the visible emission represents the entire opening angle of the open field region of the pulsar magnetosphere, we compute an emission height of only 2 km for the 1.4 GHz emission. This is below the theoretical radius for a neutron star and strongly suggests that this simple model cannot be applied in this case.

An alternative explanation comes from assuming a more conventional emission height of a few hundred km, giving a beam opening angle of $\sim 20^\circ$. In this case, only a small fraction of the beam happens to be illuminated, resulting in a narrow observed profile or we happen to be just grazing the very outer edge of the beam. In this case it is diffi-

cult to explain the double-peaked nature of the profile. If the observed pulsations are due to a grazing geometry and we assume radius-to-frequency mapping (Cordes 1978), we might expect that the pulsar would disappear at high frequencies as our line of sight no longer intersects the beam. The evolution of profile with frequency will provide valuable insight, therefore observations at other radio frequencies are warranted.

This discovery highlights the limits in our understanding of pulsar beams and shows that we may need to update our beaming models and detection probabilities for young pulsars.

5 CONCLUSIONS

Observations of three EGERT sources 3EG J1027−5817, 3EG J1800−2338 and 3EG J1810−1032 at 3.1 GHz resulted in the detection of a previously unknown young and energetic pulsar, PSR J1028−5819. The parameters of the pulsar lead us to conclude that it is likely to be the source powering 3EG J1027−5817 and we confidently expect that GLAST will detect gamma-ray pulsations from the pulsar in the near future. The pulsar is highly polarised and has an unusually narrow pulse profile.

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